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Reduction of misalignment in bonding of MEMS wafers through the use of in-situ optics

Abstract

Alignment accuracy in elevated temperature wafer bonding can be compromised by the common practice of performing the alignment outside the bonder. A new tool has been developed to allow wafers to be accurately aligned within the bonding chamber under vacuum and at high temperature. Alignment studies have been performed for anodic bonding of glass and silicon wafers. Total alignment accuracy was found to be material limited to about 5µm, due to the difference in thermal expansion between the two materials. Tool related factors accounted for <2µm of misalignment. These results, plus the ability to correct a misalignment in-situ, indicate that an integrated system can be a practical alternative to more expensive ex-situ alignment tools.

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Introduction

Device- or wafer-level bonding is a commonly used process for packaging and device assembly in MEMS technologies. For example, a silicon microstructure may be bonded to a glass substrate to isolate it from stresses arising from the packaging process. Bonding can also be used to form the microstructures themselves, for example placing a cover onto a substrate etched with channels to form microfluidic devices for use in life sciences and the pharmaceutical industry. The alignment between the surfaces to be bonded is often critical in applications where features such as through wafer vias on two or more wafers need to be matched precisely to produce the desired device performance.

Anodic bonding [1–3] is used to permanently bond glass to silicon without the use of adhesives. The alignment of the surfaces to be bonded is usually done on a separate tool, such as a modified mask alignment system [4]. The objects are then transferred to a bonding tool where the heat and high voltage are applied to create the bond. However, this practice limits the achievable bonding accuracy as the wafers can become misaligned during the application of contact force in the bonder and during the heating phase. We have developed a new bonding tool that overcomes this limitation by allowing the alignment to take place within the wafer bonder. If necessary the wafers can be separated and realigned before the bonding takes place. This paper describes the results of a study into the achievable accuracy of the in-situ alignment when bonding silicon to glass.

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Methodology

Alignment accuracy studies were performed using 12 pairs of 150mm glass and silicon wafers. The silicon wafers were oxidized on the front face and patterned with the vernier-like alignment marks shown in Figure 1(a), with 10 sets of marks distributed on the wafer as shown in Figure 1(b). The range of measurement positions was designed to allow any causes of misalignment to be more easily analyzed. The 150mm Corning 7740 glass wafers were machined with the alignment marks shown in Figure 1(c) at the same relative positions as those on the silicon wafers. Each of the 12 glass/silicon wafer pairs were put through a hydrogen peroxide/sulphuric acid “Piranha” cleaning process, which is known to reduce the incidence of voids in the bond. Each wafer was checked for flatness using a stylus profilometer over a 145mm scan parallel to the wafer flat. The silicon wafers showed a convex bow of between 20 and 46 µm, with the glass wafers showing a smaller convex bow of about 20 µm.

The bonder used in this study was an Applied Microengineering AML402. This incorporates upper and lower heated platens within the bonding chamber which can handle wafer diameters up to 200mm. The lower platen is adjustable in the x, y, z and Θ dimensions. The chamber is evacuated using a turbomolecular pump, with a working vacuum of 10^{-6} mbar achievable. The alignment optics consists of two CCD cameras mounted above viewports on either side of the vacuum chamber, as shown in Figure 2.

Wafers were manually loaded into the bonder with the silicon resting on the lower platen and the glass wafer clamped to the upper platen using a spring-loaded knife edge to push the wafer against rigid posts at the opposite side of the platen. The chamber was pumped down and once the pressure reached 10^{-3} mbar the Si wafer was raised using the z-drive mechanism until its alignment marks became visible in the alignment optics. The micro-manipulators were used to bring the Si wafer into alignment with the glass wafer before the z-drive was used to bring the two wafers into contact with each other with a force of 200N. At this stage wafer separation and realignment is still possible if the operator judges that the images of the markers on the camera monitor are misaligned. The wafers were heated to the bonding temperature of 380°C. The bonding voltage was 1000V with a current limit of 8mA. Current limited operation can produce more controllable, reproducible anodic bonding and significantly reduces the risk of electrical breakdown in the glass. The bonding time was 10 mins after which the wafers were allowed to cool to 200°C before removal.

The bonded wafers were examined using optical microscopy. Each set of alignment marks were examined and the degree of alignment accuracy determined by reading the overlapping verniers. The profilometer measurements were repeated to determine the degree of bow.

Results and discussion

The profilometer readings showed that the bonding process increased the degree of wafer bow to ~70µm, convex on the glass side.

Table 1 shows a representative sample of alignment results from the 150mm wafers. Analysis of these tables reveals that the data for X shows a difference between the left hand side (LHS) and right hand side (RHS) values of about 3 µm. This discrepancy arises out of the difference in thermal expansion between glass and silicon. The sprung knife-edge clamp sits on the wafer's RHS; therefore thermal expansion proceeds in this direction resulting in a larger change in the RHS vernier readings. Between room temperature and the bonding temperature of 380°C, the differential, expansion, ρL/L, between glass and silicon (see Figure 3) is about $80x10^{-6}$, which applied over the 70mm separation between LHS and RHS alignment marks gives 5.6 µm of differential expansion.

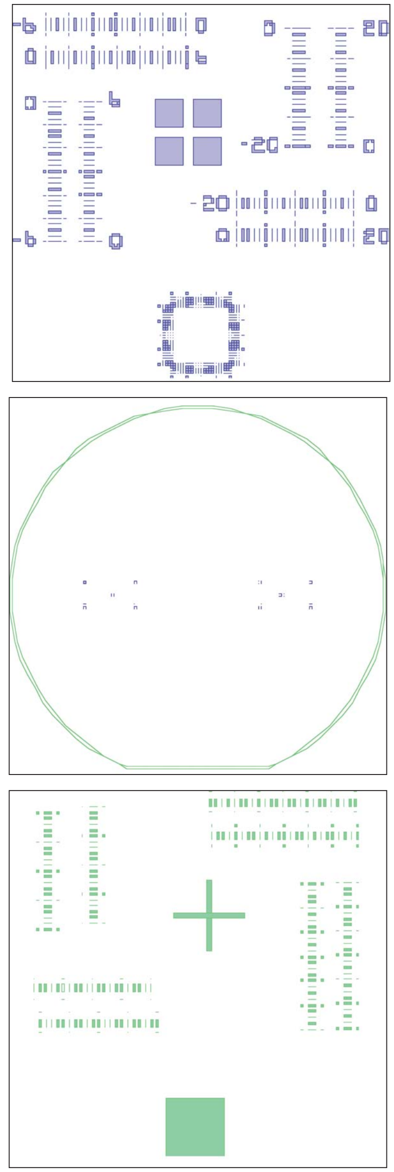

Fig 1(a)

Fig 1(b)

Fig 1(c)

Figure 1(a). Alignment marks patterned onto the silicon wafers.
Figure 1(b). Distribution map of the 10 sets of alignment marks used on the silicon and glass wafers.
Figure 1(c). Alignment patterned onto the glass wafers.

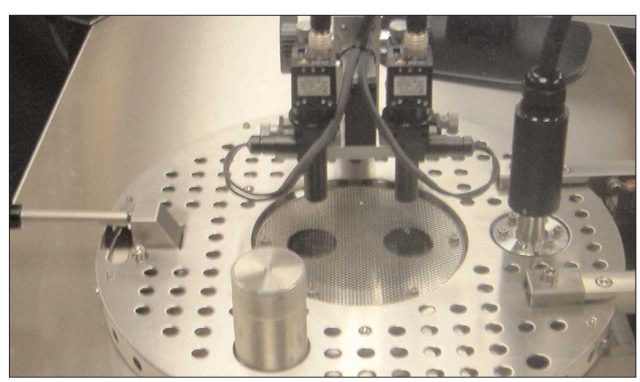

Figure 2. The lid of the vacuum chamber showing two CCD cameras mounted over the view ports.

Other factors affecting alignment accuracy include the bow of the starting wafers, which makes it difficult to simultaneously focus the alignment optics on the glass and silicon alignment marks. The indistinct nature of the edges of the marks machined directly into the glass also makes alignment difficult. There is also some movement of the silicon as the two wafers are bought together. This is likely to be a result of the wafer's bow reducing as the contact force is applied.

To investigate and quantify the impact of these factors on the alignment process, the verniers were read at different stages; before clamping; and after clamping at 300˚C, 350˚C and 400˚C. The results for a representative sample of wafers are shown in Table 2.

The table shows that the X misalignment increases as the temperature rises as would be expected from the thermal expansion coefficients for the two materials. Clamping also has an effect on the alignment, although the operator is able to separate and realign the wafers if required.

The vernier alignment data shows that the tool-related misalignment factors amount to <2μm, with the remaining misalignment resulting primarily from differences in the thermal properties between materials and not from the performance of the tool. This result, achieved with relatively simple and low-cost optics, is adequate for most microengineering bonding applications. In this case, total alignment accuracy (determined by tool-related factors plus material-related factors) of +/-2.5μm is achievable. Of course, results may vary when bonding materials with greater dissimilarities. It should be possible to compensate for the alignment runout due to thermal expansion by designing offsets into the alignment markers, and appropriate device layout, although we have yet to attempt this. Bonding below 300˚C would considerably reduce the misalignment due to thermal effects. However, it is unclear what impact this would have on the integrity of the resulting bond.

Conclusions

A wafer bonder with integrated optics that allow for in-situ wafer alignment and correction of misalignment has been evaluated. The accuracy of the system was found it to be material-limited to about +/-2.5μm for glass to silicon bonding. The in-situ alignment optics enabled the sources of misalignment to be determined and quantified by measurement at different stages of the bonding process. Thermal expansion mismatch between silicon and glass was found to be the dominant source of misalignment. Tool related factors accounted for <2μm of misalignment demonstrating the good performance of the in-situ wafer manipulator and low cost alignment optics. Given that the thermal properties of the

	Left			Right		
Wafer 6	Position	X (μm)	Y (μm)	Position	X (μm)	Y (μm)
	1	-1.0	1.5	6	-5.0	1.0
	2	-1.5	2.5	7	-4.5	1.0
	3	-2.5	1.5	8	-5.0	1.5
	4	-2.5	2.0	9	-5.5	1.5
	5	-3.0	2.5	10	-6.0	1.5

	Left			Right		
Wafer 8	Position	X (μm)	Y (μm)	Position	X (μm)	Y (μm)
	1	-4.0	2.0	6	-5.0	2.0
	2	-3.5	2.0	7	-4.5	2.0
	3	-4.0	2.0	8	-5.5	2.0
	4	-3.5	1.5	9	-6.25	2.0
	5	-3.5	2.5	10	-5.75	2.0

	Left			Right		
Wafer 11	Position	X (μm)	Y (μm)	Position	X (μm)	Y (μm)
	1	2.0	3.0	6	-2.5	1.0
	2	0.5	2.5	7	-3.0	1.0
	3	1.0	3.0	8	-3.5	1.0
	4	0.5	2.5	9	-5.0	1.5
	5	0.5	3.0	10	-5.0	1.0

Table 1. Vernier readings from 3 wafers showing the differences between the X readings between the left and the right hand sides of the wafers.

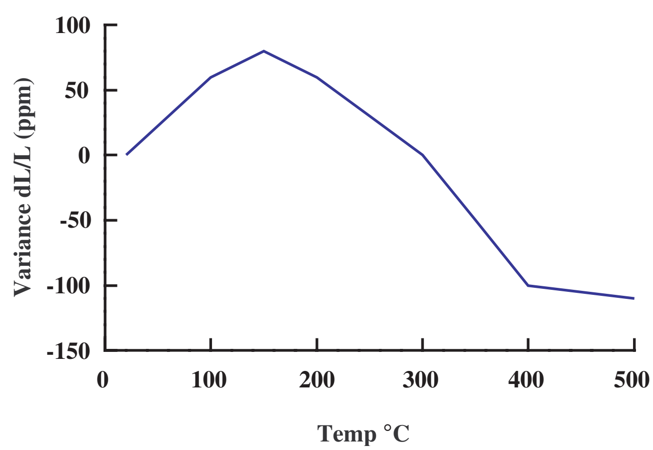

Figure 3. Thermal expansion variance for 7440 glass compared with silicon from reference [3].

materials being bonded play such a large role in determining the best possible alignment, it is questionable whether these overall results can be bettered on a practical basis by expensive ex-situ alignment tools.

References

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Wafer 6	Left (μm)		Right (μm)	
Alignment before clamping	1.0	1.0	1.0	1.0
Alignment after clamping	0	3.0	-1.0	1.5
Alignment after clamping (T=300˚C)	-1.0	3.0	-3.5	1.5
Alignment after clamping (T=350˚C)	-1.0	3.0	-4.0	1.5
Alignment after clamping (T=400˚C)	-1.0	3.0	-4.5	1.0

Wafer 3	Left (μm)		Right (μm)	
Alignment before clamping	0.0	0.5	0.0	0.0
Alignment after clamping	1.0	1.0	-2.0	2.0
Alignment after clamping (T=300˚C)	1.0	1.0	-2.0	2.0
Alignment after clamping (T=350˚C)	1.0	1.0	-2.0	2.0
Alignment after clamping (T=400˚C)	0.5	1.0	-3.5	2.0

Wafer 12	Left (μm)		Right (μm)	
Alignment before clamping	1.0	1.0	0.0	0.5
Alignment after clamping	0.5	2.5	-1.0	2.0
Alignment after clamping (T=300˚C)	0.5	2.5	-2.0	2.0
Alignment after clamping (T=350˚C)	0.5	2.5	-3.0	2.0
Alignment after clamping (T=400˚C)	1.0	2.5	-4.0	2.0

Table 2. Samples of alignment figures from three wafers at different stages of the bonding process. The misalignment becomes larger as the temperature rises.